Development Testing of the Mars Pathfinder Inflatable Landing System

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Abstract

The Mars Pathfinder lander uses a novel airbag impact attenuation system to perform its landing on Mars. Full Scale testing under Mars like atmospheric pressure conditions was performed to obtaining accurate loading conditions on the airbags during impacts on a rocky terrain. The objective was to minimize the total mass of the airbags while maximizing their performance. This paper will discuss the design of the airbags, the testing techniques used and the lessons learned from the tests. The final design of the airbag subsystem incorporates a 5 layer Vectran fabric construction with solid propellant gas generators and has a mass of 99 kg.

Introduction

In late 1993 the Jet Propulsion Laboratory began work on the Mars Pathfinder mission to land a small spacecraft and rover on the surface of Mars. The landed spacecraft concept entails a tetrahedrally shaped lander with four interconnected airbags, one per face, that completely surround and protect the lander upon impact with the Martian surface. After landing, the tetrahedron opens itself by extending its three sides like petals on a flower. This opening action ensures that the lander will always be pointing "right side up" when fully deployed.

A series of subscale proof of concept tests were performed at Sandia National Laboratory, Reference 1. Two basic types of tests were performed, vacuum chamber impact tests whereby the lander/airbags were held fixed and a moving plate was accelerated into the airbags, and canyon tests were the airbags and lander were accelerated down a

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high tension cable and released just prior to impact. These tests successfully demonstrated accurate correlation between computer models and test data.

Full Scale Design

After the success of the Sandia subscale test program, ILC Dover Inc. received a contract in August 1994 to begin work on the development of a full scale subsystem. The airbag system is comprised of four individual airbags. The three "side" airbags each vent to the base airbag via a .166 m vent. Externally, each bag resembles 6, 0.9 m radius spherical lobes pressed together on 1.0 meter centers. Internally, there is open volume with no membranes or septums. The airbag structure is held in shape and in place by way of patterning and structural tendons. Sixteen structural tendons per bag restrain the airbag and anchor it to the lander. This avoids having any fabric carry membrane loads into the lander structure. The tendons are made of 7500 pound breaking strength Vectran and Kevlar fiber rope.

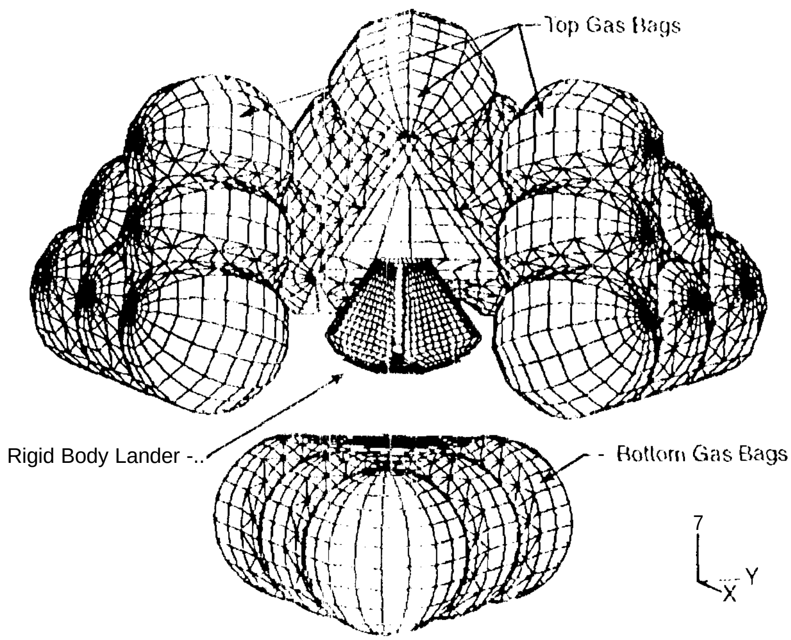

Figure 6. Exploded view of the 3D finite element model. Mode 1 created by Marc! Collier and John McKinney of Rockwell Aerospace Space Systems Division

Material Selection

Material selection was a critical part of the development cycle of the airbags. The first full scale airbag fabricated was made of urethane coated Kevlar 29. This bag however ruptured unpredictably at pressures well below it's design level. It was ultimately concluded that the high level of handling and folding of the airbag damaged the Kevlar fibers and reduced the fabric strength to unacceptable levels. At this point the switch was made from Kevlar fiber to Vectran HS fiber for the fabric. Vectran was chosen for its high strength to weight ratio, its high modulus, and its insensitivity to flex cracking of the fibers. Vectran also has high flexibility at extremely low temperatures and very high cutting and tear resistance. Vectran does not however retain its strength at elevated temperatures. For this reason Kevlar is used

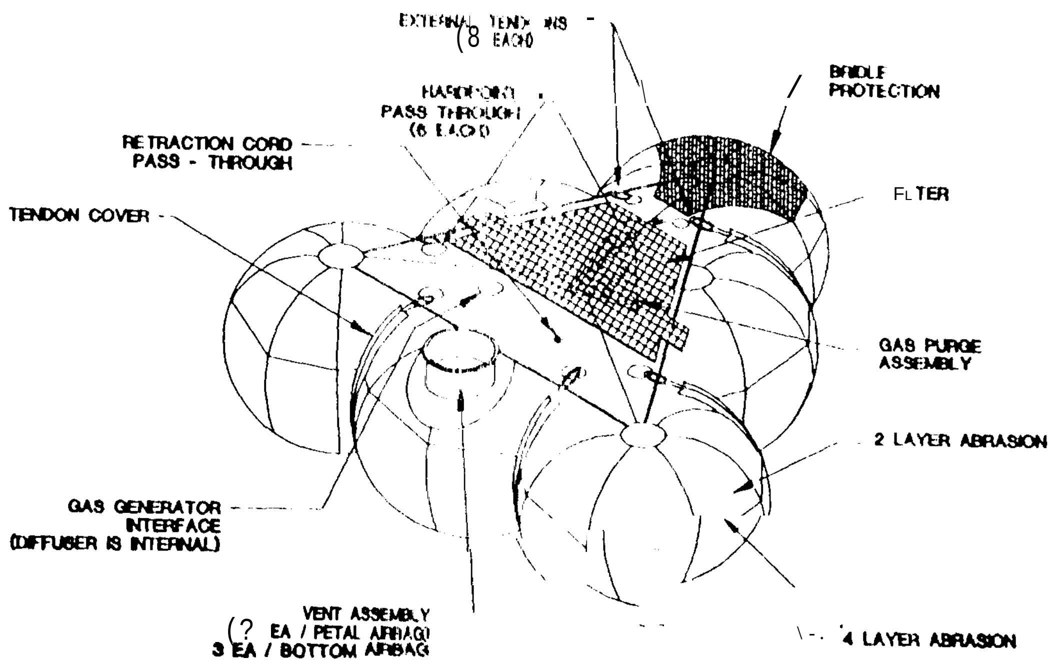

Figure 2. Single airbag assembly drawing. (Chuck Sandy)

for internal tendons and gas generator diffuser construction. In order to render the gas retaining layer airtight, a low temperature silicone formulation was applied to the inner surface of the bladder.

An interesting and important lesson learned in the development of the bladder weave/construction was that the lubricating effect of the sizing agent was critical in attaining the highest, and necessary, tear strength performance of the fabric. In most applications the sizing is scoured off after weaving, yet for this application it was necessary to specify a specific amount of sizing agent to be left on the fabric. Vacuum stability of the sizing agent must then be considered with respect to mission constraints. After a great deal of trial and error and close work with the fabric weaving house the bladder cloth was specified as follows:

200 denier Vectran HS fiber	
50x50 yarns per inch	2.7 oz./yrd^2
Calendared post weaving	
Silastic LT-50 silicone rubber coating	1.6 oz./yrd^2
Total fabric weight	4.3 oz./yrd^2

It was also desired to use Vectran HS for the construction of an outer layer of fabric to protect the bladder layer from rock damage. This layer is called the abrasion layer. The design and sizing of the abrasion layer was done incrementally. Early tests were done by dropping "Mars like" lava rocks at 20 m/s onto candidate samples inflated to achieve representative skin loading. Subsequent tests were done in an instron machine whereby a sharp rock was slowly pressed into an inflated dome with proper skin loading, and the load at the point of bladder rupture was recorded. Both forms of testing were highly qualitative but they revealed some very important trends. Reference 2 discusses some of the results.

None of the analytical approachs used early on were adequate or applicable in determining the highly complicated loading of the abrasion layer during a skidding impact with a sharp random rock field. The only reliable method of determining the best and lightest abrasion layer construction was full scale testing onto actual rocks. To do this, three full scale test series were designed to optimize the abrasion layer construction and demonstrate landing capability on 0.5 meter high rocks.

Full Scale Drop Testing

As was realized early on in the testing of the subscale airbags at Sandia, it is necessary to conduct impact testing in a Mars like near-vacuum environment in order to attain the correct compression ratios and skin stresses. NASA Lewis Plum Brook station Space Power Facility (SPF) was selected as the test facility since it has the largest vacuum chamber in the US. The chamber measures 120 feet high by 100 feet in diameter. A test platform measuring 48 x 28 feet was built to provide a controlled landing surface. In the first three tests the platform was mounted horizontal and with no rocks. For all subsequent tests the platform was populated with lava rocks ranging from .2 to .5 meters high, and mounted at a 60 degree angle to simulate a 30 degree impact on Mars.

Drops below 20 m/s impact velocity could be performed by simply allowing the entire system to free fall the appropriate distance in the near vacuum environment. The worst case test requirement however was for a 28 m/s impact onto the 60 degree platform. This and any test above 20 m/s required the use of an accelerator device. A 60 foot long bungie system with multiple pullies was built to achieve impact velocities between 20m/s and 28 m/s. Figure 2 shows the SPF chamber and the drop test set up.

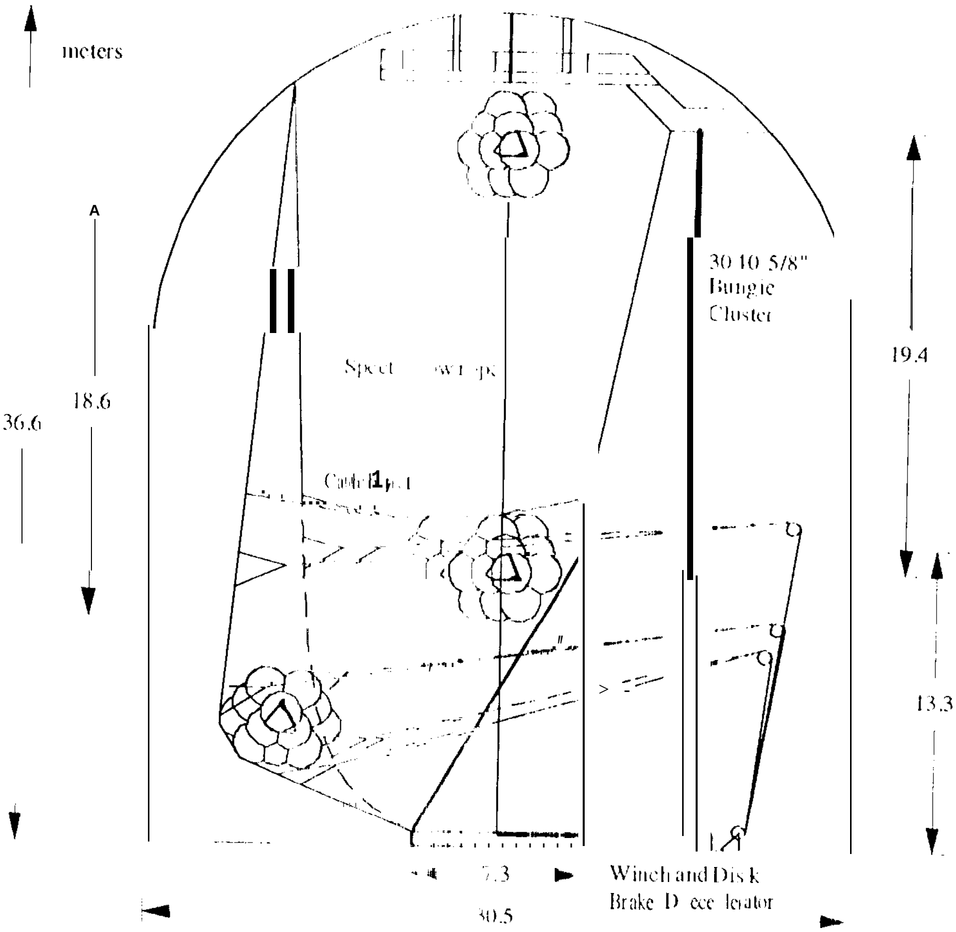

Figure 2. NASA Lewis Plum Brook Station SPF Vacuum chamber full scale drop test setup layout.

Prototype Test Series

The first test series was called the prototype 1 test series. The main objectives of these tests was to generate load and dynamic data required to validate analytical models, to demonstrate impact capability at various impact angles and velocities and to determine if the initial design of the abrasion layer sizing was adequate. The abrasion layer consisted of a single layer of 200 denier 45x45 ypi (yarns per inch) Vectran HS fabric woven in a 2-1-1-2 modified ripstop weave and patterned 4% larger than the bladder layer. In order to conserve mass, abrasion layer was only applied to the portion of the airbags that were uncovered by other portions of the airbags. In all, 57% of the airbag surface area was covered. The mass of the airbag system was 54kg. Table 1 gives the summary of the tests performed.

Table 1. Prototype 1 drop test summary.

Drop #	Velocity (m/s)	Rock Size (m)	Pressure (psig)	Platform	Orientation
1	15	0	1.5	horizontal	base bag first
2	15	0	.155	horizontal	side bag
3	20	0	1.5	horizontal	side bag
4	15	.5	1.5	60 degrees	side bag
5	20	.5	1.5	60 degrees	side bag

After very successfully performing test 1 through 3 it was decided that the single layer abrasion layer would most likely be inadequate to handle the sloped, rocky impact. Retrofit abrasion layer panels were fabricated to replace the specific abrasion layer gores that would come into contact with the rocks on drops 4 and 5. The test approach allowed the targeting of very specific regions of the airbag. Four abrasion layer concepts were constructed.

1. 200 denier 113x71 ypi Kevlar fabric
2. 400 denier Vectran HS 53x53 ypi
3. 1 layer of 45x45 2112 modified ripstop weave Vectran fabric quilted to a .10 inch thick Kevlar nonwoven felt.
4. two layers of 45x45 2112 ripstop weave Vectran fabric oriented 45 degrees to each other.

Test numbers 4 and 5 showed that the heavy Kevlar fabric performed poorly under direct impact with rocks. The 400 denier Vectran fabric only received glancing blows, but seemed promising. The quilted construction and the double layered construction both performed adequately by scraping off major portions of their outer layers thereby protecting the bladder layer. None of the abrasion layer constructions proved to be conclusively adequate. Test number 5 also resulted in a massive rupture of an airbag where it struck one of the three .5 meter rocks on the platform. The seam failure was caused in part by the expedient field method used to attach the retrofitted abrasion gores.

Each of the 5 tests produced a full set of data. Each tendon of bag number 1 was instrumented with in line load cells to measure the tendon tension. The pressure and temperature of the gas in the bags was measured. Accelerometer data was recorded in order to understand the full 6 axis dynamic performance of the lander inside the airbag system. A summary of this data can be found in reference 3.

Armed with a wealth of performance data for each of the abrasion layer constructions tested in prototype 1, a second test series was prepared to test the two most promising constructions. The quilted Kevlar felt construction was dropped due to its high volumetric requirements for stowage. The starting configuration of the airbag system for prototype test 2 was; bags 1 and 2 used two plies of the 45x45 Vectran ripstop weave fabric, and bags 3 and 4 used a single layer of the 400 denier plain weave Vectran fabric. This time 67% of the airbag surface area was covered by abrasion layer again patterned 4% larger than the bladder. Two contingency bags were fabricated with a heavier bladder layers in the event that neither of the primary airbags proved adequate. The two other constructions were; bag 5 used a 65x65 ypi, 200 denier plain weave bladder layer coupled with 2 plies of 45x45 Vectran ripstop fabric, bag 6 also used the heavier 65x65 bladder layer but it was coupled to the heavier 400 denier plain weave abrasion layer. The prototype 2 bag as well as all the other bags and test specimens were all subjected to a minimum bake cycle of 6 hours at 125 deg C prior to any structural testing in order to simulate the effects that the planetary protection heat sterilization would eventually have on the final flight system.

Table 2. Prototype 2 drop test summary

Drop [redacted]	Velocity (m/s)	Rock Size (m)	Pressure (psig)	Platform	Orientation
6	16	.55	.5	60 degrees	2dn, 1tr
7	16	.55	.5	60 degrees	3dn, 4tr
8	22.85	.33	.5	60 degrees	3dn, 4tr
[redacted]	[redacted]2.85	.33	.0	60 degrees	6dn, 5tr
[redacted]	22.30	.3	.92	60 degrees	4dn, 5&6tr
[redacted]	26.64	.55	.89	60 degrees	2dn, 6tr
12 [redacted]	[redacted].81	.55	.92	60 degrees	6dn, 2tr

Note: the orientation refers to which bag was facing in the direction of motion, ie down (dn), and which bag was essentially trailing (tr), ie facing the platform thus making grazing but hard contact with the platform and its rocks.

Drops 6 and 7 both showed acceptable performance of the tested abrasion layers. Drop 8 however resulted in massive tearing of abrasion and bladder layers in most areas that came in direct contact with rocks. As a result of drop 8 it was decided to incorporate bags 5 and 6. Since the proto. 1 tests showed a greater stroke margin than anticipated it was also decided to reduce the inflation pressure to help decrease the static membrane stress and thus increase resistance to rock tear. Drops 9 and 10 both showed improved performance. Large tears up to 6 and 8 inches in length still rendered these constructions unacceptable.

After drop 10 it was decided to make up another set of retrofit abrasion gores to replace entire lobes, and perform 2 more tests in order to finalize a construction. The new constructions were as follows; two lobes used a combination of the 53x53 400 denier Vectran fabric and the 45x45 2112 ripstop fabric over a 50x50 bladder, another two lobes used 3 plies of the 45x45 2112 ripstop Vectran fabric each with its yarns oriented 45 degrees to each other, over a 50x50 bladder, and yet another two lobes used the 53x53 400 denier Vectran fabric with a 4 inch cross hatch grid of 1/4 inch Kevlar webbing.

Drops 11 and 12 both showed excellent performance. Virtually no tearing of the bladder layer occurred in the newly reinforced areas. The general performance trend indicated that the combination of 53x53 and 45x45 abrasion layer performed well for the first impact but left large sections with the single layer of 53x53 abrasion layer bare. The 53x53 abrasion layer with the Kevlar grid also performed well but did have the tendency of starting multiple short tears that did not damage the underlying bladder layer but left it vulnerable. The best performer was the triple 45x45 abrasion construction. In all cases only the top 1 or 2 layers were ever damaged. The third layer and underlying bladder layer were never damaged.

By virtue of having coated each rock on the platform with colored chalk powder it became evident rocks were able to contact the bare bladder layer beyond the 67% coverage line. This observation led to increasing coverage to 100% of the airbag, excluding portions protected by the lander structure.

The prototype 2 test series showed conclusively that a three layered abrasion layer would adequately protect the airbags during impact. The decision was made to baseline an airbag system with 4 layers of the 45x45 2112 Vectran fabric. The fourth layer was added to ensure adequate layers would always be available even after multiple impacts on the same spot. Figure 3 shows a typical seam cross section.

The Full Scale Development (FSD) test was subseqently prepared to show that the airbag system could be inflated in under 2.0 seconds with a gas generator system and subsequently survive multiple impacts on the same test platform. Four gas generators designed and built by Thiokol corporation were integrated onto the drop test lander and airbags at the Plum Brook test facility. The airbags were packed in a very precise pattern and held tightly to the lander via a specially designed pyrotechnically released fabric cover. The highly instrumented package was then lowered into a 35x85 foot cryogenic vacuum chamber and chilled to -85 deg. C. The inflation was performed by first activating the pyrotechnic cable cutters on the packing cover, followed .25 seconds later by the ignition of three of the 4 gas generators. The airbags fully inflated and pressurized in under .75 seconds. The fourth gas generator was fired 20 seconds

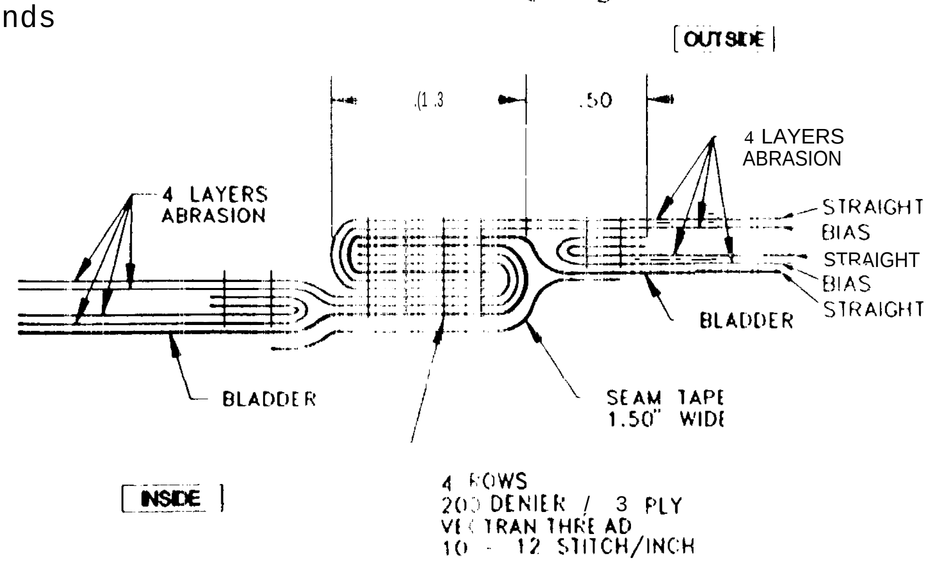

Figure 3. Sample seam layout.

later to make up for lost pressure due to cooling effects. The inflation test was nearly flawless and induced no damage to the airbags whatsoever. Following the inflation test 3 more drop tests were performed.

Table 3. FSD drop test summary.

Drop #	Velocity (m/s)	Rock Size (m)	Pressure (psig)	Platform
FSD 1	28.03	.5	.92	60 degrees
FSD 2	25.40	.3	.94	60 degrees
FSD 3	23.96	.5	.91	60 degrees

The results of the FSD drop tests identified a number of areas requiring some minor reinforcement, but overall proved extremely successful. Table 3 summarizes the FSD drop tests.

ROCK DISTRIBUTION

The rock distribution of the test platform was recorded and compared to the Viking 1 and 2 landing site distributions. JPL's Matt Golombek states the following:

"In all cases, the rock distributions for which the airbags have been tested represent extreme conditions. The total area covered by rocks in the airbag test surfaces, when extrapolated parallel to Viking rock distributions are a factor of 2 or 3 greater than any surfaces on Mars indicated by the thermal inertia (orbital) data. With regard to large rocks greater than 1 m diamet er and/ or 5 met ers high potent ially hazardous to landing , t he I est si t es had over 10% of thei r surfaces cov ered compared wi th 1 ess than 1% of the surface at VI 2. The rock distributions against which the airbags have been test ed represent the worst possible conditions pot ent ia 1 ly possible on Mars. . . "

CONCLUSIONS

By way o f fu l l scale drop t est i ng under representative pressure and i mpact condi tion s , a wealth of data, both qualit ative and quantitative, Was gathered about_ p] anetary inf l atable impact at t enuat i on design. The test program center ed on a gradual and opt i mal evolution of the abrasi on l aye r system. Of tile numer ous abrasion 1 ayer concepts f abri cated and t est ed the combi nati on of mu] tiple, thin layers of high st rength Vect ran fabric: proved super ior. The FSD tests al so demonst rated that the a i rbag system coul d withstand a c old temperature rapid inflation in uncle] . 75 seconds wi thou t damaging the ai rbags and then st i 1 l survive mul t. iple i mpact s on rocks with margin . The final design of t he airbag system has a total fabric mass of 87 Kg and gas generator mass of 12 kg, the t otal l anded mass is 1 (10 Kg . The ai rbag drop test. surface conditi ons were 2 to 3 t imes more severe than anythi ng i ndicated by surface or orbi t al data and "represent the worst possible condi t i ons potentially possi bl e on Mars . "

A c kn owl edgments

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